Advanced Isolation Design
for Avionics on Launch Vehicles

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Report Documentation Page

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ABSTRACT

Research to create advanced vibration isolator designs and practical design techniques for Launch Vehicle (LV) manufacturers is discussed. Avionics of launch vehicles have unique requirements for isolation since many generate heat and cannot use convection cooling for dissipation. Nearly all isolation systems are ineffective thermal conductors unless expensive custom modifications are performed. The cost of a custom isolation design can rarely be justified, particularly with expendable vehicles. While viscoelastic isolators offer simplicity and affordability, such materials with high loss factors (greater than 0.25) also exhibit aggressive changes in stiffness with both temperature and frequency. Materials having new and unique formulations are introduced which have an order of magnitude higher thermal conductivity than today's materials of similar stiffness. This enables appreciable heat conduction with nominal temperature increases to isolated packages. The formulation of nearly all elastomeric vibration isolators creates heavy coupling between their loss factors and the rate of change in their storage moduli. High loss factors result in an aggressive temperature-dependent shift in the resonant frequencies of an isolated element. New compounds introduced in this paper address this limitation. A software utility has also been developed that greatly simplifies isolation design. The utility solves the equations of motion for a rigid body on flexible mounts and allows performance predictions using base vibration inputs. New progress in material technology and design techniques enables LV manufacturers to implement affordable designed vibration isolation systems on avionics and similar systems.

Keywords: Vibration isolation, launch vehicle avionics, avionics isolation, viscoelastic materials

1. INTRODUCTION

Avionics of launch vehicles present unique requirements for vibration isolation since many generate heat and cannot use convection cooling for dissipation. Millions of dollars are spent every year to harden avionics to loads seen in flight, yet vibration isolation could be an effective alternative if isolators exhibited low impedance to heat flow. Expendable launch vehicles also require inexpensive isolators that can be integrated by the vehicle manufacturer with practical design procedures. This paper documents research to address these needs.

Viscoelastic isolators offer the cost-effective vibration isolation required by expendables. Research performed at CSA Engineering has identified high thermal conductivity compounds with mechanical properties that are suitable for vibration isolators. The formulation of nearly all elastomers for vibration isolators creates heavy coupling between their loss factors and the rate of change in their storage moduli with respect to temperature. The result is an aggressive temperature-dependant shift in the resonant frequencies of an isolated element. New compounds introduced in this paper greatly reduce this temperature sensitivity.

An isolation design utility has been created to improve the design capabilities available to vehicle manufacturers. Commercial isolators are typically selected based on crude sizing estimates and without understanding of cross-axis performance. This utility solves the equations of motion for a rigid body on flexible mounts and allows performance predictions, such as transmissibility and acceleration spectra of the payload motion, using user-defined base vibration inputs.

2. PROBLEM DEFINITION

Needs for improvements in vibration isolation were taken from CSA's experience and feedback from several launch vehicle manufacturers. Specifically, the feedback from vehicle manufacturers indicated the following needs:

1. Thermally conductive vibration isolators for avionics that dissipate heat.
2. Isolator materials with a nearly constant storage modulus and a high loss factor over a large temperature range.
3. A design tool that can accurately predict vibration isolation performance.

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The subsections below address each of these needs sequentially.

1. The Need for Thermally Conductive Systems

Isolation systems are effective heat blocks. Table 1 shows the typical values of thermal transmissions through isolators that are common today. Specifications for heat load from the most demanding avionics are also shown. The heat conducted for a temperature difference of 30 degrees Fahrenheit is far below the required rate.

Avionics type and form of vibration isolator	Avionics weight (lbf)	Frequency for Isolation Modes (Hz)	Coef. Of Thermal Conductivity (W/m C)	Required heat load (Watts)	Heat conduction with isolators 30 °F $\mathbb{D}$T (Watts)
Large power supplies* elastomer isolators wirerope isolators	80 80	70 below 70	0.2 -	200 200	13.6 3.3
Small avionics with elastomer isolators	5	70	0.2	5 - 20	0.4

* worst case example of actively cooled avionics

Table 1: Common vibration isolators and their thermal permeativity

Several techniques can augment the conductivity of elastomer forms:

1. Material conductivity can be increased.
2. Thermal shunt paths can be installed.

Thermal shunts require additional elements and a high standard of care by the user and manufacturer. Measurements at CSA have demonstrated that their permeability can be greatly inhibited by contact resistance. Data acquired by CSA has indicated that viscoelastic isolators are not subject to the same constraints because they are soft and readily fill the air voids that interrupt heat flow. While viscoelastic isolators can minimize contact resistance, their conductivity remains unacceptably low.

Recent efforts have focused on compounding since it offers the greatest potential for improvement. Primary goals are to generate compounds that exhibit high conductivity and low storage modulus or hardness. Materials with low storage moduli permit larger cross-sectional areas per unit stiffness. Larger cross-sectional areas permit higher heat permeativity.

The electronics industry has created a large market for conductive polymers. However, these materials are intended to fill voids between hard surfaces in contact and do not have the mechanical properties required by applications in vibration isolation.

2. The Need for Thermally Insensitive Materials with High Loss Factors

The performance of a vibration isolation system is determined by the mass properties of the isolated element, isolator complex stiffness in each of three directions, and the position and orientation of isolator elements. Since the strain energy of isolation modes is completely within the isolators, the structural damping will be the loss factor of the isolator material. Clearly the material properties of isolators can heavily constrain the design.

Most viscoelastics used for vibration isolation today follow a model for their complex modulus that is well understood. Elastomers are commonly materials that are in a temperature and frequency range where their behavior is called "rubbery." This term refers to one of three phases encountered near a glass transition region.

Unmodified viscoelastics only exhibit high loss factors in regions where a glass transition region exists, or near melting. The properties of two common elastomers are shown in Figure 1 and Figure 2 throughout their glass transition regions. These curves, called reduced frequency nomograms, are generated with a shifting function that overlays ranges of temperature and

frequency that produce identical mechanical behavior [1]. The plot enables a designer to interpolate and extrapolate to temperatures and frequencies that were not acquired.

The qualities needed for most vibration isolation applications are found in the rubbery region. Shifts with temperature and frequency are moderate, and materials can tolerate large strains without damage. Material behavior becomes brittle in the glassy region, and changes in storage modulus through glass transition are often too aggressive.
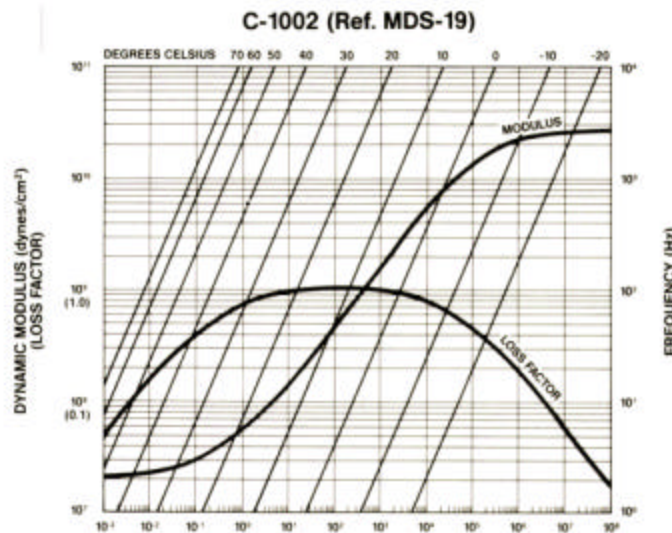
Figure 1: Reduced frequency nomogram of EAR C1002 in shear

Several properties become obvious upon inspection of Figure 1. The maximum loss factor occurs in glass transition. Also, the storage modulus in shear changes most rapidly at the center of glass transition. The results can be generalized for unmodified materials; the higher the loss factors at a temperature and frequency, the greater the shift in storage modulus.

The problem of temperature sensitivity in viscoelastic materials can be minimized using a material that exhibits only shallow changes in glass transition, and that has a glass transition that is centered about the desired temperature and frequency range. Finding such a material can be a difficult if not impossible task.

A common urethane, PR1570, is presented as an example of an unmodified polymer with a limited variation through glass transition. The reduced frequency nomogram of PR1570 is shown in Figure 2. Peak loss factor is less than 0.50 for this material, meeting the criteria established above of a shallow glass transition.

Consider an application requiring a Q of less than or equal to 3. This requires a material loss factor of 0.33 or greater. PR1570 meets the requirement at 3 Hz over a span of less than 70 degrees with temperatures ranging from 52 to 120 degrees Fahrenheit. Variation in shear modulus is 10 to 1 through this span and total variation through glass transition is greater than 100 to 1. Isolator resonant frequencies would shift by the square root of 10 within a temperature window of 70 degrees Fahrenheit, and by 10 to 1 through the entire temperature range. Clearly, variations in storage modulus will cause intolerable mistuning of the isolation mode frequencies for avionics and or space applications with wide temperature fluctuations.

In summary, heavily damped viscoelastic materials exhibit large variations in their storage modulus with temperature and frequency making them less desirable for some applications.
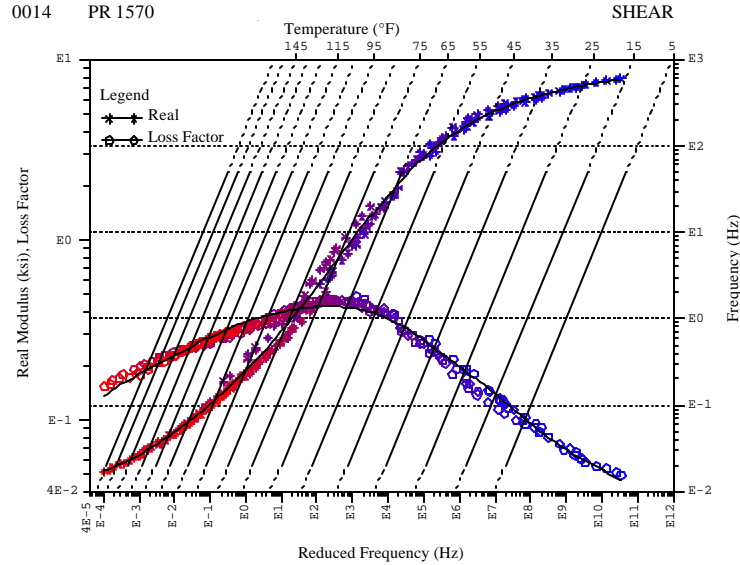
Figure 2: Reduced frequency nomogram for PR1570 Urethane

3.   The Need for an Isolation Design Tool

The tools used to design isolation systems are currently limited to single degree-of-freedom (SDOF) methods found in catalogs or via finite element analysis (FEA). FEA is often too expensive for preliminary design. The SDOF design methods used in catalogs are rarely accurate because vibration excitation sources are typically not unidirectional. For example, if the center of gravity of the payload is not in line with the center of the force applied by the isolators, more than one mode will contribute to the transmissibility in the horizontal direction. An example of this case is shown in Figure 3. Two modes dominate the transmissibility in the lateral direction since horizontal forces heavily excite both. Their resonant frequencies are also quite different, making the transmissibility exhibit the worst properties of both the higher and lower frequency modes. The result is far from that predicted by the single degree-of-freedom isolation problem.

The example problem shown in Figure 3 is a common package layout. The cube shows dimensions of the package while the dashed lines extend from the Center of Gravity (CG) of the isolated body to the isolator landings, a total of four.
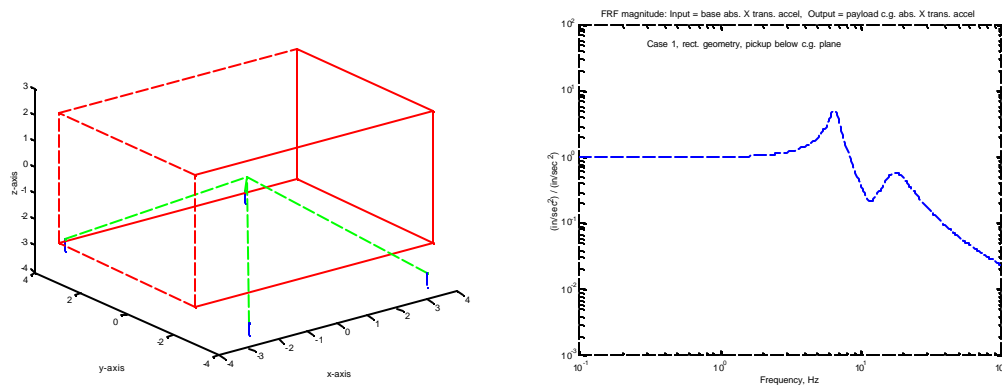

Figure 3: Horizontal excitation of example payload

Coupling between translation and rotation is neglected with a SDOF model. Design handbooks provide charts for determining some of these modes, but they are typically limited to specific geometries with the isolator at the extreme corners of the payload. Furthermore, predicted performance from the SDOF case is non-conservative. Transmission ratios exhibit the worst qualities of both modes. The lower frequency mode elevates transmissibility at low frequencies, generating larger

strains on the isolator and rattle space requirements. The higher frequency mode elevates transmission at high frequencies where the low-frequency mode alone would permit very low transmission ratios.

3. RESULTS

1. Compounding for Thermal Conductivity

Materials were formulated that exhibit conductivity far greater than existing compounds. Figure 4 shows data from several materials including materials compounded by CSA. The compounds formulated by CSA exhibit conductivity that is an order of magnitude greater than unmodified elastomers of similar hardness.
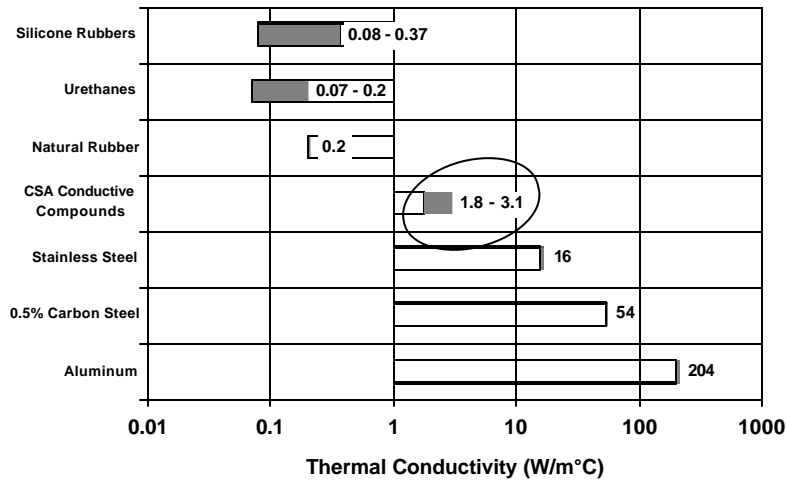
Figure 4: Conductivity of CSA's new materials shown against others for reference

While several materials have been formulated to date, efforts are continuing to generate materials that exhibit both higher conductivity and desirable mechanical properties. Table 2 shows some of the compounds formulated to date including their thermal conductivity. Conductivity levels of the modified compounds are nominally a decade greater than the available compounds to date.

Compound name	Hardness	Thermal Conductivity (W/m C)	Notes
CSA ISO101	40	2.3	high damping, max. loss factor of 0.40
CSA ISO102	35	3.1	light damping
CSA ISO103	45	2.1	inexpensive, light damping
CSA ISO104	45	1.8	inexpensive, moderate damping

Table 2 - Materials modified for elevated thermal conductivity

Material properties were the focus of this research since they determine so much of the conduction rate for isolators, but the end goal is to increase conduction through viscoelastic isolators. Predictions are presented in Table 3 to show the power flow enabled by conductive isolator designs. Results are better than a decade of improvement from the rates of existing isolators since geometric improvements also provided gains. In the more demanding applications examined by CSA, heat flow is adequate with the high-conductivity isolators with a temperature difference of 30 degrees Fahrenheit. In most applications, the avionics dissipate less heat than the "required" column in Table 3, and a less conductive compound could be used.

Avionics type and form of vibration isolator	Avionics weight (lbf)	Frequency for Isolation Modes (Hz)	Coef. Of Thermal Conductivity (W/m C)	Required heat load (Watts)	Heat conduction with CSA ISO102 30 °F DT (Watts)
Large power supplies* elastomer isolators	80	70	3.1	200	211.1
Small avionics with elastomer isolators	5	70	3.1	5 - 20	18.4

* worst case example of actively cooled avionics

Table 3 - Parameters predicted for conductive isolators

Conductivity data presented in Table 2 was acquired at CSA on a system that was designed in accordance with the ASTM standard E1225-87 on thermal conductivity testing using the guarded hot plate method.

Materials formulated by CSA are generally between 25 and 45 Shore A hardness. As mentioned previously, materials with low moduli (or hardness) can occupy a larger cross-sectional area per unit stiffness, increasing heat flow. However, lower modulus materials are also lower density, and generally have lower conductivity on this basis alone.

2. Compounding for Temperature Insensitivity

Compounds were developed at CSA that have high loss factors and little variations with temperature and frequency.
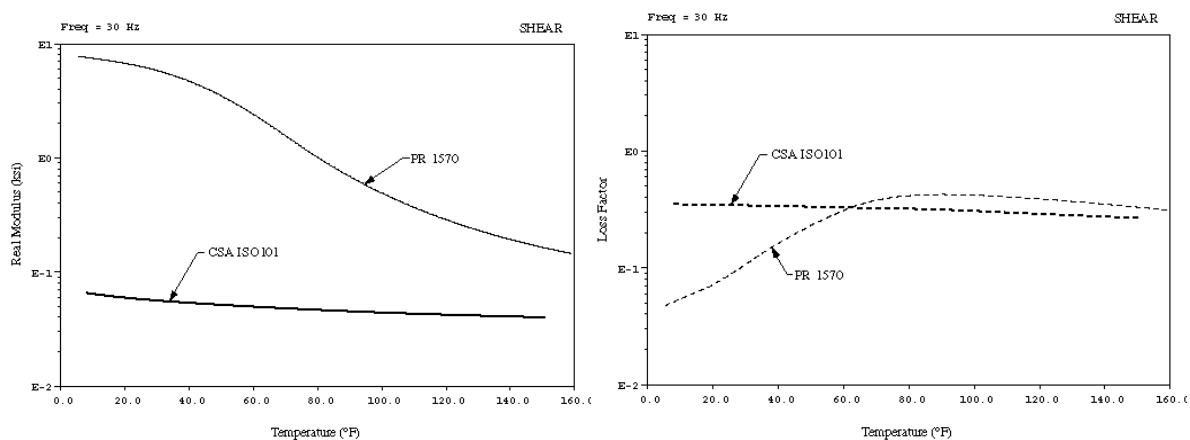
Figure 5 - Overlay of CSA ISO101 material with an unmodified material that has similar loss

Constant frequency plots for CSA ISO101 are presented in Figure 5 along with an unmodified material, PR1570 urethane, that has similar loss levels. Shear modulus of PR1570 varies by over 50 to 1 throughout the temperature extremes while CSA ISO101 changes by less than 2 to 1. Similar stability is seen in the loss factor of CSA ISO101 while the PR1570 varies by 10 to 1. Peak loss of the PR1570 is .45, while the peak of CSA ISO101 is 0.40. The average loss factor of CSA ISO101 is, on average, the same over a wide temperature window.

A reduced frequency nomogram of CSA ISO101 is included in Figure 6 to describe other properties. Temperature-frequency superposition properties still apply, making a clean curve on the nomogram at low strain levels. Stability over such wide temperature and frequency windows is unavailable with unmodified high-loss elastomers.

Furthermore, the CSA compounds can be "tuned" to exhibit a target loss factor with simple and repeatable changes in the formulation. Several modifications of the CSA ISO101 formulation have been generated. Loss factors can be decreased to 0.10 with little consequence to storage modulus. Higher loss factors are also likely possible, but have not yet been formulated. Applications in vibration isolation rarely require a loss factor above 0.40.

Amplitude dependence of the CSA compounds is unclear and is currently being explored. Modified isolator materials may exhibit nonlinearities, particularly at high-strain levels. The results presented in Figure 6 were acquired at a zero-to-peak dynamic shear strain amplitude of 1.5 %.
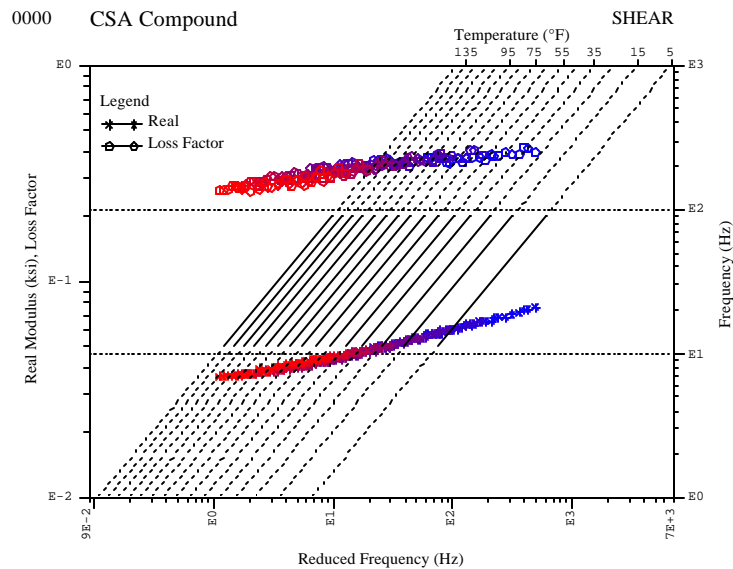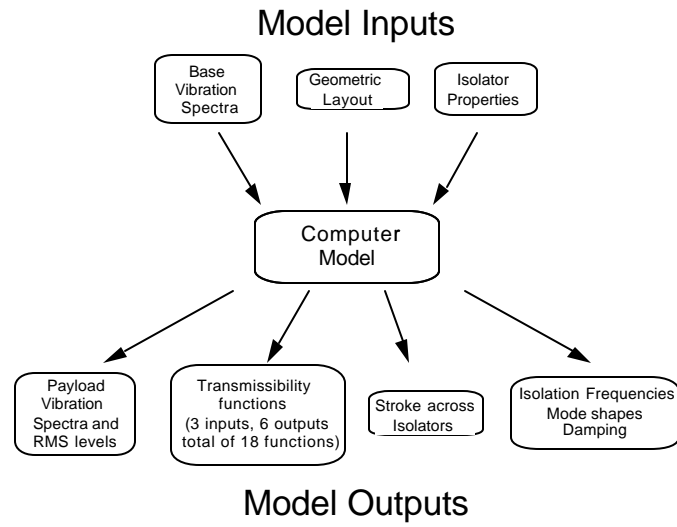

Figure 6: Reduced frequency nomogram for CSA ISO101 compound

3. Design Tool

The software design tool is a work-in-progress computer program that solves the six equations of motion for a rigid body suspended on flexible mounts [2]. The software is a stand-alone executable that runs within Matlab. The modeled system is a rigid body mounted on an arbitrary number of resilient mounts. The sequence of operations is shown in Figure 7. The software provides fast yet comprehensive set of tools needed by the vibration isolation designer for common applications. The "isolator properties" input in Figure 7 is provided for elements made by CSA Engineering. The designer need only know the geometric layout (including mass properties) of the system to model. Base vibration spectra are optional. Vibration spectra and RMS levels on the isolated payload are output only if input spectra are provided.

Model Inputs

Base Vibration Spectra

Geometric Layout

Isolator Properties

Computer Model

Payload Vibration Spectra and RMS levels

Transmissibility functions (3 inputs, 6 outputs total of 18 functions)

Stroke across Isolators

Isolation Frequencies Mode shapes Damping

Model Outputs

Figure 7 - Schematic of the work flow using the design tool

The principal stiffness axes of the mounts can be oriented in any direction with respect to the global coordinate system, as can the principal inertia axes of the rigid payload. The P and Q axes define the transverse directions of the mounts. The R axis defines the orientation of the mount.

Isolators can have different stiffness and damping in the P, Q, and R directions. Differential stiffness effects include the destabilizing influence of the change in force direction of finite-length struts preloaded by payload weight. For each strut, this amounts to a negative stiffness in each of the two transverse directions. Transverse stiffness k_p and k_q are set equal to $-P_{oi}/L_i$ where P_{oi} and L_i are the preload and length of the i'th strut.

Arbitrary locations/directions can be specified for external force inputs applied directly to the payload. Arbitrary locations can be specified on the payload for motion output DOFs. The six DOFs of the center of gravity (CG) are always output.

The coordinate system must be rectangular. The payload CG location is arbitrary and is specified just like the isolator connection points relative to the payload.

Each mount is assumed to have damping in the form of a dashpot in parallel with the axial stiffness. When preloading effects are included, damping and stiffness matrices are no longer proportional so mode shapes need not be real.

The design tool is written in Matlab from The Mathworks. A user of the tool must have access to the Matlab environment. All geometric parameters are set by the user in a Matlab script file. The isolator properties are likewise set in a separate script file. The parameter script file is executed in Matlab and a figure showing the problem geometry is displayed, as seen in Figure 3. The solver script is then run and frequency response function (FRF) plots for the isolator design are produced. FRF plots for the CG of the simple system in Figure 3 are shown in Figure 8.

The multiple DOF solution from the design tool demonstrates that this design is far from optimal in all directions other than translation in the Z direction (normal to the base plane). The lateral translation isolation modes, seen in the first and second plots of Figure 8, are not close in frequency. Large frequency differences can create problems if the modes are well excited. Low frequency modes generate larger deflections, and therefore, increase rattle space requirements. Higher frequency modes disturb the isolation attenuation that would be offered by lower frequency modes. The multiple DOF isolation design tool indicates problems with isolation designs that cannot necessarily be uncovered with SDOF estimates.
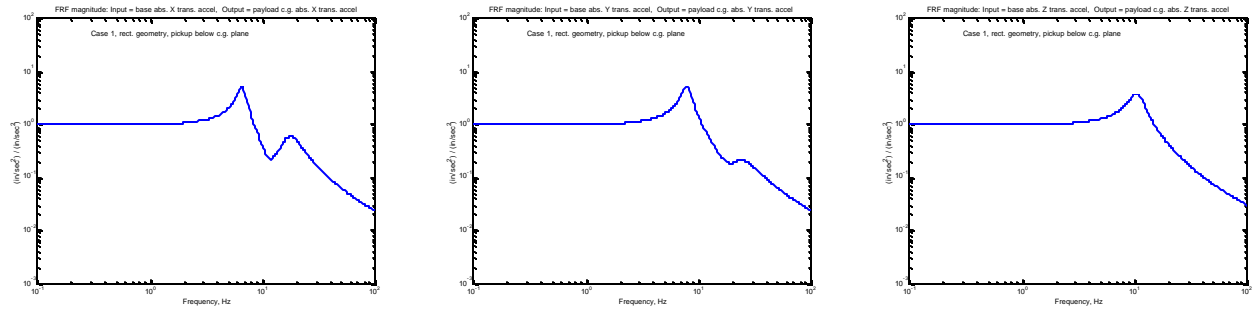
Figure 8: Frequency response in X, Y, and Z directions

There is also provision in the design tool for calculating the acceleration response at the CG (PSD and RMS) for specified base acceleration PSDs in the X, Y, and Z direction. The base acceleration PSDs may be measured data or may be specified in log-line form. That is, they are defined by a series of straight lines on a log-log plot of acceleration PSD versus frequency. Output PSD units are consistent with the input (usually g^2/Hz). Figure 9 shows the input and calculated response PSDs for the sample payload in Figure 3. For this sample case, reduction in RMS response given the same input PSD is calculated at 80.45%, 80.32%, and 78.51% for the X, Y, and Z directions, respectively.
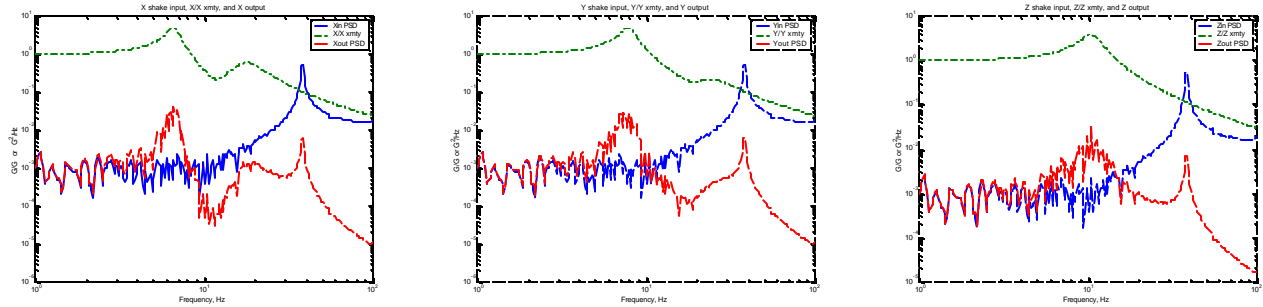

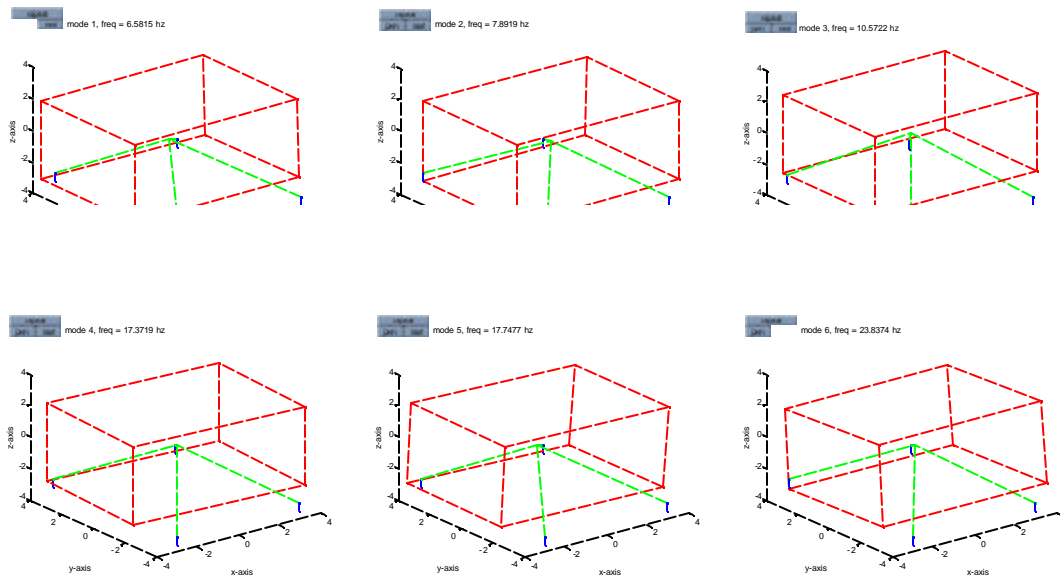Figure 9: Input and predicted response PSDs

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Figure 10: First six mode shapes of a sample isolated system

4. CONCLUSIONS

Research is presented that offers performance enhancements in thermal conductivity of isolator materials, the stability of their moduli with temperature and frequency, and design techniques for isolation systems. Thermal conductivity improvements make vibration isolation practical for nearly all avionics systems. New materials have also been generated to reduce variations in storage moduli and loss factors while retaining large loss factors. Finally, an analytical design tool is presented that enables transmissibility prediction using by solving the equations of motion in all six degrees of freedom. The tool also provides the capability to predict other parameters such as acceleration spectra of the payload motion and stroke across isolator elements.

5. ACKNOWLEDGEMENTS

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